

$$\begin{aligned}
& + \sum_{n,q} \text{COALLOWSUL}_{n,q} \cdot \text{lowsuladd\_LCF}_n \cdot \text{CHeatRate}_q \\
& \quad \text{[surcharge for using low sulfur coal]} \\
& + \text{RPS\_shortfall} \cdot \text{RPSSCost} \\
& + \sum_{states} \text{St\_RPSshortfall}_{states} \cdot \text{St\_RPSSCost} \\
& + \sum_{states} \text{St\_CSPRPSshortfall}_{states} \cdot \text{St\_CSPRPSCost}_{states} \\
& \quad \text{[costs of shortfalls in failing to meet RPS requirements]}
\end{aligned}$$

## A.4 Constraints

The minimization of cost in ReEDS is subject to a large number of different constraints, involving limits on resources, transmission constraints, national growth constraints, ancillary services, and pollution. Unless specifically noted otherwise (see, for example, the wind resource limit below), these constraints apply to new generating capacity built in the time period being optimized.

The constraint name is shown with the subscripts over which the constraint applies. For example, in the constraint immediately below, the subscript ‘ $c, i, l$ ’ immediately following the name of the constraint implies that this constraint is applied for every class of wind  $c$ , every region  $i$ , and every location  $l$ . Because there are 356 regions, five classes of wind, and 3 locations, this first type of constraint is repeated 5,340 times (356x5x3).

### A.4.1 Constraints on Wind

**Wind Resource Constraint:** For every wind class  $c$  and wind supply region  $i$ , the sum of all wind capacity installed in this and preceding time periods must be less than the total wind resource in the region.

$WIND\_RES\_UC_{c,i,l}$

$$\text{WturN}_{c,i,l} + \text{WturTN}_{c,i,l} + \text{Wtur\_inregion}_{c,i,l} \leq \max(0, \text{WRuc}_{c,i,l} - \text{WturO}_{c,i,l} - \text{WTturO}_{c,i,l})$$

**Wind Supply Curve:** New wind of class  $c$  in region  $i$  at interconnection cost step  $wscp$  must be less than the remaining wind resource in that cost step.<sup>9</sup> The second constraint balances the wind on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

$WIND\_supply\_curves_{c,i,l,wscp}$

$$\text{WturN}_{c,i,l,wscp} \leq \max(0, \text{WR2G}_{c,i,l,wscp})$$

$WIND\_EXISTRANS\_BALANCE_{i,l}$

$$\sum_{wscp} \text{WNSC}_{i,l,wscp} = \sum_j \text{WN}_{i,j,l}$$

<sup>9</sup>A preliminary optimization is performed outside and prior to the main model to construct a supply curve for onshore wind, shallow offshore wind, and deep offshore wind for each wind class  $c$  and region  $i$ . This supply curve is comprised of four quantity/cost pairs ( $\text{WR2G}_{c,i,l,wscp} / \text{WR2GPTS}_{c,i,l,wscp}$ ). The “curve” provides the amount of class  $c$  wind  $\text{WR2G}_{c,i,l,wscp}$  that can be connected to the pre-2006 grid for a cost between  $\text{WR2GPTS}_{c,i,l,wscp-1}$  and  $\text{WR2GPTS}_{c,i,l,wscp}$ . This “pre-LP” optimization is described in more detail in Appendix G. The quantity  $\text{WR2G}_{c,i,l,wscp}$  is reduced after each period’s LP optimization by the amount of wind used in the time period from that cost step.

**Wind Transmission Constraint:** The new class  $c$  wind transmitted from a region  $i$  to all regions  $j$  must be less than or equal to the total amount of new region  $i$  class  $c$  wind used from the class  $c$  wind supply curve.

$WIND\_2\_GRID_{c,i,l}$

$$\sum_j WN_{c,i,j,l} \leq \sum_{wscp} WturN_{c,i,l,wscp}$$

$WIND\_2\_NEW_{c,i,l}$

$$\sum_j WTN_{c,i,j,l} \leq \sum_{wscp} WturTN_{c,i,l,wscp}$$

$WIND\_INREGION_{c,i,l}$

$$\sum_{escp} Welec\_inregion_{c,i,l,escp} \leq Wtur\_inregion_{c,i,l}$$

**Wind Growth Constraint:** These two constraints allocate new wind capacity (MW) to bins that have turbine prices that are higher than the costs during periods of rapidly growing demand. The bins are defined as a fraction of the national wind capacity (MW) at the start of the period.

$WIND\_GROWTH\_TOT$

$$\sum_{c,i,l} (WturN_{c,i,l} + WturTN_{c,i,l} + Wtur\_inregion_{c,i,l}) \leq \sum_g WCt_g$$

$WIND\_GROWTH\_BIN_g$

$$WCt_g \leq Gt_g \cdot BASE\_WIND$$

**Wind Installation Growth Constraint:** These two constraints allocate new wind capacity (MW) to bins that have installation costs associated with them over and above the base costs of installation. The bins are defined as a fraction of the regional wind capacity (MW) at the start of the period.

$WIND\_GROWTH\_INST_i$

$$\sum_{c,l} (WturN_{c,i,l} + WturTN_{c,i,l} + Wtur\_inregion_{c,i,l}) - 200 \leq \sum_{ginst} WCtinst_{i,ginst}$$

$WIND\_GROWTH\_BIN\_INST_{i,ginst}$

$$WCtinst_{i,ginst} \leq Gtinst_{ginst} \cdot BASE\_WIND\_inst_i$$

**Wind Curtailments:** This constraint defines wind curtailments based on a statistical approach. SurplusOld and SurplusMar are calculated in between investment periods based on a statistical approach and as described in Appendix D. The last term on the right hand side reduces the amount of curtailed wind power if new storage is built in balancing area  $n$ .  $WSurpLess_{n,m}$  is then subtracted from the wind contribution to meeting the  $LOAD\_PCA$  constraint for time-slice  $m$  and for the RPS requirement.

$WIND\_RECOVERY_{n,m}$

$$\begin{aligned}
WSurpLess_{n,m} &\geq SurplusOld_{n,m} \\
&+ \sum_{c,i,j,l}^{j \in n} (WN_{c,i,j,l} + WTN_{c,i,j,l} + Welec\_inregion_{c,j,l}) \cdot (1 - TWLOSSnew \cdot Distance_{ij}) \cdot SurplusMar_{n,m} \\
&- \sum_{st} SurplusRecoveryPerStorage_{n,m} \cdot STOR_{n,st}
\end{aligned}$$

#### A.4.2 Constraints on CSP

**CSP Resource Limit:** For every CSP class and supply region  $i$ , the sum of all CSP capacity installed in this and preceding time periods must be less than the total solar resource in the region.

$CSP\_REC\_UC_{cCSP,i}$

$$\begin{aligned}
&CSPTurN_{cCSP,i} + CSPTurTN_{cCSP,i} + \\
&CSPTur\_inregion_{cCSP,i} \leq \max(0, CSPRuc_{cCSP,i} - CSPTurO_{cCSP,i} - CSPTurO_{cCSP,i})
\end{aligned}$$

**CSP Supply Curve:** New CSP of class  $cCSP$  in region  $i$  at interconnection cost step  $cspscp$  must be less than the remaining solar resource in that cost step. The second constraint balances the CSP on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

$CSP\_supply\_curves_{cCSP,i,cspscp}$

$$CSPTurN_{cCSP,i,cspscp} \leq \max(0, CSP2G_{cCSP,i,cspscp})$$

$CSP\_EXISTRANS\_BALANCE_i$

$$\sum_{cspscp} CspNSC_{i,cspscp} = \sum_j CspN_{ij}$$

**CSP Transmission Constraints:** New CSP transmitted from a region  $i$  to all regions  $j$  must be less than or equal to the total amount of new region  $i$  CSP used from the solar supply curve.

$CSP\_2\_GRID_{cCSP,i}$

$$\sum_j CSPN_{cCSP,i,j} \leq \sum_{cspscp} CSPTurN_{cCSP,i,cspscp}$$

$CSP\_2\_NEW_{cCSP,i}$

$$\sum_j CSPTN_{cCSP,i,j} \leq \sum_{cspscp} CSPTurTN_{cCSP,i,cspscp}$$

$ELEC\_inregion_{cCSP,i}$

$$\sum_{escp} CSPELEC\_inregion_{cCSP,i,escp} \leq CSPTur\_inregion_{cCSP,i}$$

**CSP Growth Constraint:** These two constraints allocate new CSP capacity (MW) to bins that have plant costs associated with them over and above the costs of the solar plants themselves. The bins are defined as a fraction of the national CSP capacity (MW) at the start of the period.

$$CSP\_GROWTH\_TOT$$

$$\sum_{cCSP,i} (CSPturN_{cCSP,i} + CSPturTN_{cCSP,i} + CSPtur\_inregion_{cCSP,i}) \leq \sum_{gCSP} CSPCt_{gCSP}$$

$$CSP\_GROWTH\_BIN_{gCSP}$$

$$CSPCt_{gCSP} \leq GtCSP_{gCSP} \cdot BASE\_CSP$$

**CSP Installation Growth Constraint:** These two constraints allocate new CSP capacity (MW) to bins that have installation costs associated with them over and above the base costs of installation. The bins are defined as a fraction of the regional CSP capacity (MW) at the start of the period.

$$CSP\_GROWTH\_INST_i$$

$$\sum_{cCSP} (CSPturN_{cCSP,i} + CSPturTN_{cCSP,i} + CSPtur\_inregion_{cCSP,i}) - 200 \leq \sum_{gCSPinst} CSPCtinst_{i,gCSPinst}$$

$$CSP\_GROWTH\_BIN\_INST_{i,gCSPinst}$$

$$CSPCtinst_{i,gCSPinst} \leq GtCSPinst_{gCSPinst} \cdot BASE\_CSP\_inst_i$$

### A.4.3 General Renewable Constraints

**State RPS Requirement:** This allows the model to include state Renewable Portfolio Standards (RPS), wherein the total annual renewable generation must exceed a specified fraction of the state electricity load or a penalty must be paid on the shortfall.

$ST\_RPSConstraint_{states}$

$St\_RPSfraction_{states}$

$$\begin{aligned}
\sum_{n,m}^{n \in states} L_{n,m} \cdot H_m &\leq \sum_{c,i,j,m,l}^{j \in states} (WN_{c,i,j,l} + WTN_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
&\quad \cdot (1 - TWLOSS_{new} \cdot Distance_{i,j})(1 - SurplusMar_{c,j}) \\
&+ \sum_{c,i,j,m}^{j \in states} (WO_{c,i,j,l} + WTO_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
&\quad \cdot (1 - TWLOSS_{old} \cdot Distance_{i,j})(1 - SurplusOld_{c,j}) \\
&+ \sum_{c,j,m}^{j \in states} Welec\_inregion_{c,j,l} \cdot CF_{c,j,m,l} \cdot H_m \\
&\quad \cdot (1 - SurplusMar_{c,j}) \\
&+ \sum_{cCSP,i,j,m}^{j \in states} (CSPN_{cCSP,i,j} + CSPTN_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
&\quad \cdot (1 - TWLOSS_{new} \cdot Distance_{i,j}) \\
&+ \sum_{cCSP,i,j,m}^{j \in states} (CSPO_{cCSP,i,j} + CSPTO_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
&\quad \cdot (1 - TWLOSS_{old} \cdot Distance_{i,j}) \\
&+ \sum_{cCSP,j,m}^{j \in states} CSPElec\_inregion_{cCSP,j} \cdot CF_{cCSP,m} \cdot H_m \\
&+ \sum_{c,i,m,st}^{j \in states} (WSTORin\_wind_{c,i,m,st} + old\_WSTORin\_wind_{c,i,m,st}) \cdot H_m \\
&+ \sum_{n,m}^{n \in states} (CONV_{n,m,geothermal} + CONVP_{n,m,geothermal}) \cdot H_m \\
&+ \sum_{n,m}^{n \in states} (CONV_{n,m,biopower} + CONVP_{n,m,biopower}) \cdot H_m \\
&+ \sum_{bioclass,n} CofireGen_{bioclass,n} \\
&- \sum_{n,m}^{n \in states} WSurpLess_{n,m} \cdot H_m \\
&+ St\_RPS\_Shortfall
\end{aligned}$$

**RPS Requirement:** This allows the model to include a national Renewable Portfolio Standard.

RPSConstraint

RPSfraction

$$\begin{aligned}
& \left( \sum_{c,i,j,m,l} (\text{WN}_{c,i,j,l} + \text{WTN}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot H_m \right. \\
& + \sum_{c,i,j,m,l} (\text{WO}_{c,i,j,l} + \text{WTO}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot H_m \\
& + \sum_{c,j,m,l} \text{Welec\_inregion}_{c,j,l} \cdot \text{CF}_{c,j,m,l} \cdot H_m \\
& + \sum_{cCSP,i,j,m} (\text{CSPN}_{cCSP,i,j} + \text{CSPTN}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{cCSP,i,j,m} (\text{CSPO}_{cCSP,i,j} + \text{CSPTO}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{cCSP,j,m} \text{CSPelec\_inregion}_{cCSP,j} \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{n,m,q} (\text{CONV}_{n,m,q} + \text{CONVP}_{n,m,q}) \cdot H_m \\
& + \sum_{n,m} (\text{STORout}_{n,m,\text{CAES}} - \text{STORin}_{n,m,\text{CAES}}) \cdot H_m \\
& - \sum_{n,m} \text{WSurpLess}_{n,m} \cdot H_m \Big) \\
& \leq \sum_{c,i,j,m,l} (\text{WN}_{c,i,j,l} + \text{WTN}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot H_m \\
& + \sum_{c,i,j,m,l} (\text{WO}_{c,i,j,l} + \text{WTO}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot H_m \\
& + \sum_{c,j,m,l} \text{Welec\_inregion}_{c,j,l} \cdot \text{CF}_{c,j,m,l} \cdot H_m \\
& + \sum_{cCSP,i,j,m} (\text{CSPN}_{cCSP,i,j} + \text{CSPTN}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{cCSP,i,j,m} (\text{CSPO}_{cCSP,i,j} + \text{CSPTO}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{cCSP,j,m} \text{CSPelec\_inregion}_{cCSP,j} \cdot \text{CF}_{cCSP,m} \cdot H_m \\
& + \sum_{n,m} (\text{CONV}_{n,m,\text{hydro}} + \text{CONV}_{n,m,\text{fill}} + \text{CONV}_{n,m,\text{distPV}}) \cdot H_m \\
& + \sum_{n,m} (\text{CONV}_{n,m,\text{geothermal}} + \text{CONVP}_{n,m,\text{geothermal}}) \cdot H_m \\
& + \sum_{n,m} (\text{CONV}_{n,m,\text{biopower}} + \text{CONVP}_{n,m,\text{biopower}}) \cdot H_m \\
& + \sum_{\text{bioclass},n} \text{CofireGen}_{\text{bioclass},n} \\
& - \sum_{n,m} \text{WSurpLess}_{n,m} \cdot H_m \\
& + \text{RPS\_Shortfall}
\end{aligned}$$

**Limits on Existing Transmission:** Due to extant transmission capacity usage and other limitations, the amount of wind power able to be transported on pre-2006 lines is limited. This constraint limits the wind imports on pre-2006 lines to some fraction of the capacity of the transmission lines crossing the boundaries of demand region  $j$ .

$WIND\_interregion\_trans_j$

$$\sum_{c,l} (WN_{c,i,j,l} + WO_{c,i,j,l}) - \sum_{c,l} (WN_{c,j,j,l} + WO_{c,j,j,l}) + \sum_{cCSP,i} (CspN_{cCSP,i,j} + CspO_{cCSP,i,j}) - \sum_{cCSP} (CspN_{cCSP,j,j} + CspO_{cCSP,j,j}) \leq \sum_k a_k \cdot Tk_k$$

**Regional Balancing Constraint:** This constraint is a transmission capacity balance that defines the transmission capacity needed to handle wind and CSP transmission between balancing authorities. This transmission capacity required for wind/CSP is combined with that required by conventional generation to identify bottlenecks between balancing authorities. The left-hand side of the constraint is the sum of all wind and CSP generation transmitted into the balancing authority plus all that generated within. The right-hand side is the sum of all the wind and CSP generation consumed in- plus all that transmitted from the balancing authority.

$WIND\_BALANCE\_PCAS_n$

$$\begin{aligned} & \sum_p ReT_{n,p} + \\ & \sum_{c,i,j,l}^{i \in n} (WN_{c,i,j,l} + WO_{c,i,j,l}) + \\ & \sum_{cCSP,i,j}^{i \in n} (CspN_{cCSP,i,j} + CspO_{cCSP,i,j}) = \sum_p ReT_{p,n} \\ & + \sum_{c,i,j,l}^{j \in n} (WN_{c,i,j,l} + WO_{c,i,j,l}) \\ & + \sum_{cCSP,i,j}^{j \in n} (CspN_{cCSP,i,j} + CspO_{cCSP,i,j}) \end{aligned}$$

**Conventional Transmission Constraint:** Ensures that there is sufficient transmission capacity between contiguous balancing authorities  $n$  and  $p$  within the same grid interconnect to transmit wind generation and conventional generation in each time-slice  $m$ . Transmission capacity added this period is included in both directions  $p$ -to- $n$  and  $n$ -to- $p$  because transmission lines are bidirectional.<sup>10</sup>

$CONV\_TRAN\_PCA_{n,p,m}$

$$CONVT_{n,p,m} + ReT_{n,p} \leq TPCAN_{n,p} + TPCAN_{p,n} + TPCAO_{n,p}$$

<sup>10</sup>The  $ReT_{n,p}$  variable prevents ReEDS from shipping wind or CSP from supply region  $i$  to the closest demand region  $j$ ; and, from there, continue to ship it as conventional power to other balancing authorities where generation is needed. The problem with this is that if new lines are required for this extended wind transmission to a different balancing authority, the wind will not have to pay for a dedicated transmission line, i.e. the transmission line cost will be spread over more hours than only those during which the wind blows.

**Contracted Transmission Constraint:** Ensures that there is sufficient transmission capacity between contiguous balancing authorities  $n$  and  $p$  within the same grid interconnect to transmit wind generation and contracted conventional capacity. Transmission capacity added this period is included in both directions  $p$ -to- $n$  and  $n$ -to- $p$  because transmission lines are bidirectional.

$$CONTRACT\_TRAN\_PCA_{n,p}$$

$$CONTRACTcap_{n,p} + WT_{n,p} + CspT_{n,p} \leq TPCAN_{n,p} + TPCAN_{p,n} + TPCAO_{n,p}$$

**Transmission Growth Constraints:** These two constraints allocate new transmission capacity (MW) to bins that have costs associated with them over and above the cost of the transmission lines themselves. The bins are defined as a fraction of the national transmission capacity at the start of the period.

$$TPCA\_GROWTH\_TOT$$

$$TPCAN_{n,p} + \sum_{c,i,j} WTN_{c,i,j} + \sum_{cCSP,i,j} CspTN_{cCSP,i,j} \leq \sum_{TPCA_g} TPCA\_Ct_{TPCA_g}$$

$$TPCA\_GROWTH\_BIN_{TPCA_g}$$

$$TPCA\_Ct_{TPCA_g} \leq TPCA\_Gt_{TPCA_g} \cdot BASETPCA$$

#### A.4.4 Constraints on System Operation

**Generation Requirement:** This constraint ensures that the load (MW) in time period  $m$  in balancing authority  $n$  is met with power from conventional and renewable generators plus net imports from balancing authorities contiguous to  $n$  ( $CONVT_{n,p,m}$ ). Long-distance transmission from wind and CSP facilities and imports are decremented for transmission losses. Wind and CSP output are also decreased by wind curtailments. Storage can also contribute, but the charging of storage adds to the load requirement.

The *LOAD\_PCA* constraint is the constraint that is affected by the mini-slices; for  $(n, m)$  pairs that qualify, it is split into three independent constraints (each with a different set of wind capacity factors) that must be dispatched separately.



$LOAD\_PCA_{n,m}$

$$\begin{aligned}
L_{n,m} \leq & \sum_q (\text{CONVgen}_{n,m,q} + \text{CONVP}_{n,m,q}) \\
& + \sum_p (\text{CONVT}_{p,n,m} \cdot (1 - \text{TWLOSS} \cdot \text{Distance}_{n,p}) - \text{CONVT}_{n,p,m}) \\
& + \sum_{c,i,j}^{j \in n} (\text{WN}_{c,i,j,l} + \text{WTN}_{c,i,j,l}) \cdot \text{CF}_{c,i,m,l} \cdot (1 - \text{TWLOSS}_{\text{new}} \cdot \text{Distance}_{i,j}) \\
& + \sum_{c,j,l}^{j \in n} \text{Welec\_inregion}_{c,j,l} \cdot \text{CF}_{c,j,m,l} \\
& + \sum_{c,i,j,l}^{j \in n} (\text{WO}_{c,i,j,l} + \text{WTO}_{c,i,j,l}) \cdot \text{CFO}_{c,i,m,l} \cdot (1 - \text{TWLOSS}_{\text{old}} \cdot \text{Distance}_{i,j}) \\
& - \text{WSurpLess}_{n,m} \\
& + \sum_{cCSP,i,j}^{j \in n} (\text{CSPN}_{cCSP,i,j} + \text{CSPTN}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot (1 - \text{TWLOSS}_{\text{new}} \cdot \text{Distance}_{i,j}) \\
& + \sum_{cCSP,j}^{j \in n} \text{CSPelec\_inregion}_{cCSP,j} \cdot \text{CF}_{cCSP,m} \\
& + \sum_{cCSP,i,j}^{j \in n} (\text{CSPO}_{cCSP,i,j} + \text{CSPTO}_{cCSP,i,j}) \cdot \text{CF}_{cCSP,m} \cdot (1 - \text{TWLOSS}_{\text{old}} \cdot \text{Distance}_{i,j}) \\
& + \sum_{st} (\text{STORout}_{n,m,st} - \text{STORin}_{n,m,st})
\end{aligned}$$

**Reserve Margin Requirement:** Ensures that the conventional and storage capacity (MW) and capacity value of wind and CSP during the peak summer period is large enough to meet the peak load plus a reserve margin and any storage input requirements. Peak-load requirements in NERC region  $r$  can also be met by contracting for capacity located in other NERC regions.

$$RES\_MARG_{rto}$$

$$\begin{aligned}
\sum_n^{n \in rto} P_{rto} \cdot (1 + RM_{rto}) &\leq \sum_{n,q}^{n \in rto} CONV_{n,q} \\
&+ \sum_{c,i,j}^{j \in rto} (WN_{c,i,j} + WTN_{c,i,j}) \cdot CVmar_{c,i,rto} \\
&\quad \cdot (1 - TWLOSS_{new} \cdot Distance_{i,n}) \\
&+ \sum_{c,i,j}^{j \in rto} (WO_{c,i,j} + WTO_{c,i,j}) \cdot CVold_{c,i,rto} \\
&\quad \cdot (1 - TWLOSS_{old} \cdot Distance_{i,n}) \\
&+ \sum_{c,j,escp}^{j \in rto} Welec\_inregion_{c,j,escp} \cdot CVmar_{c,i,rto} \\
&+ \sum_{cCSP,i,j}^{j \in rto} (CspN_{cCSP,i,j} + CspTN_{cCSP,i,j}) \cdot CspCVmar_{cCSP,i,rto} \\
&\quad \cdot (1 - TWLOSS_{new} \cdot Distance_{i,n}) \\
&+ \sum_{cCSP,i,j}^{j \in rto} (CspO_{cCSP,i,j} + CspTO_{cCSP,i,j}) \cdot CspCVold_{cCSP,i,rto} \\
&\quad \cdot (1 - TWLOSS_{old} \cdot Distance_{i,n}) \\
&+ \sum_{cCSP,j,escp}^{j \in rto} CSpelec\_inregion_{cCSP,j,escp} \cdot CspCVmar_{cCSP,i,rto} \\
&+ \sum_{n,st}^{n \in rto} STOR_{n,st} + old\_STOR_{n,st} \\
&+ \sum_{i,st}^{i \in n} WSTORout\_inregion_{i,H16,st} + old\_WSTORout\_inregion_{i,H16,st} \\
&+ \sum_{n,p}^{n \in rto} CONTRACTcap_{p,n} \cdot (1 - TLOSS \cdot Distance_{n,p}) \\
&- \sum_{n,p}^{n \in rto} CONTRACTcap_{n,p}
\end{aligned}$$

**Operating Reserve Requirement:** Ensures that the spinning reserve, quick-start capacity, and storage capacity are adequate to meet the normal operating reserve requirement and that imposed by wind. The second and third constraints work together to ensure that no more than a set fraction ( $qsfrac$ ) of the operating reserve requirement be met by quickstart capacity.

$$OPER\_RES_{rto,m}$$

$$\begin{aligned} Oper\_Res\_Req_{rto,m} \leq & \sum_{n,q}^{n \in rto} SR_{n,m,q} + QS_{n,q} \cdot F_q \\ & + \sum_{n,st}^{n \in rto} STOR\_OR_{n,m,st} + \sum_{i,st}^{i \in rto} WSTOR\_OR_{i,m,st} + old\_WSTOR\_OR_{i,m,st} \end{aligned}$$

$$OPER\_RES2_{m,rto}$$

$$\begin{aligned} Oper\_Res\_Req_{rto,m} = & TOR_{rto,m} \\ & + \sum_{c,j}^{j \in rto} (WN_{i,j} + WTN_{i,j}) \cdot ORmar_{c,i,rto,m} \\ & + \sum_{c,j}^{j \in rto} Welec\_inregion_{c,j} \cdot ORmar_{c,j,rto,m} \end{aligned}$$

$$OPER\_RES3_{rto,m}$$

$$\sum_{n,q}^{n \in rto} QS_{n,q} \cdot F_q \leq qsfrac \cdot Oper\_Res\_Req_{rto,m}$$

**Spinning Reserve Constraint:** Ensures that the useful generation from a conventional plant of type  $q$  comprises at least a minimum fraction of the total generation in time-slice  $m$  in balancing authority  $n$ .

$$SPIN\_RES\_CAP_{n,m,q}$$

$$SR_{n,m,q} \leq CONVgen_{n,seasonpeak,q} \cdot FSRV_q$$

**Capacity Dispatch Constraint:** Ensures that the capacity (MW) in balancing authority  $n$  of type  $q$ —derated by the average forced outage rate for type  $q$  generators—is adequate to meet the load, quick-start, and spinning reserve required in time-slice  $m$ .

$$CAP\_FO\_PO_{n,m,q}$$

$$CONVgen_{n,m,q} + SR_{n,m,q} + QS_{n,q} \leq CONV_{n,q} \cdot (1 - FO_q)(1 - PO_{m,q})$$

**Peaking Constraint:** To prevent unrealistic cycling, base-load plants are constrained in peak time-slices to generate no more electricity than the average of that which is generated in the shoulder time-slices. Additional power is available through  $CONVP$ , at increased cost.

$B\_peak\_12_{n,m,q}$

$$\begin{aligned}
CONVgen_{n,H3,q \in baseload} &\leq (CONVgen_{n,H2,q \in baseload} + CONVgen_{n,H4,q \in baseload})/2 \\
CONVgen_{n,H7,q \in baseload} &\leq (CONVgen_{n,H6,q \in baseload} + CONVgen_{n,H8,q \in baseload})/2 \\
CONVgen_{n,H12,q \in baseload} &\leq (CONVgen_{n,H10,q \in baseload} + CONVgen_{n,H11,q \in baseload})/2 \\
CONVgen_{n,H15,q \in baseload} &\leq CONVgen_{n,H14,q \in baseload} \\
CONVgen_{n,H16,q \in baseload} &\leq (CONVgen_{n,H2,q \in baseload} + CONVgen_{n,H4,q \in baseload})/2
\end{aligned}$$

**Minimum Load Constraint:** To prevent baseload plants from ramping down to unrealistic levels, minimum power output can not fall below a set fraction of peak power output.

$MIN\_LOADING_{n,m,q}$

$$CONVgen_{n,m,q} + CONVP_{n,m,q} \geq CONVgen_{n,seasonpeak,q} \cdot minplantload_q$$

#### A.4.5 Constraints on Storage

**Energy Balance:** Energy discharged from storage type  $st$  in each area  $i$  or  $n$  must not exceed the energy used to charge storage—multiplied by the round-trip efficiency for type  $st$  generators—within a single season.

$ENERGY\_FROM\_GRID\_STORAGE_{n,s,st}$

$$\sum_{m \in s} STORout_{n,m,st} \cdot H_m \leq \sum_{m \in s} STORin_{n,m,st} \cdot H_m \cdot STOR\_RTE_{st}$$

**Storage Dispatch Constraint:** Ensures that storage capacity of type  $st$ —derated by the average forced outage rate for type  $st$  generators—is adequate to supply all charging power, discharging power, and operating reserve demanded in each time-slice  $m$ .

$STORE\_FO\_PO\_GRID_{n,m,st}$

$$STORout_{n,m,st} + STORin_{n,m,st} + STOR\_OR_{n,m,st} \leq (STOR_{n,st} + old\_STOR_{n,st})(1 - FO_{st})(1 - PO_{m,st})$$

**Storage Growth Constraint:** These two constraints allocate new storage capacity (MW) to bins that have costs associated with them over and above the cost of the storage capacity itself. The bins are defined as a fraction of the national storage capacity at the start of the period.

$STORAGE\_GROWTH\_TOT_{st}$

$$\sum_n STOR_{n,st} \leq \sum_{storagebp} STORAGEBIN_{st,storagebp}$$

$STORAGE\_GROWTH\_BIN_{st,storagebp}$

$$STORAGEBIN_{st,storagebp} \leq STORAGEBINCAP_{st,storagebpt} \cdot BASE\_STORAGE_{st};$$

#### A.4.6 Others

**Hydropower Energy Constraint:** Restricts the energy available from hydroelectric capacity to conform to the historical availability of water.

$$HYDRO\_ENERGY_n \quad \sum_m CONVgen_{n,m,hydro} \leq Hen_n$$

**California Coal Restriction:** Western states can generate no more energy from coal or ogs (plants that are dirtier than gas-cc) than they can consume in-state. This is to prevent them from shipping coal-generated electricity to California.

$$CALIFORNIA\_COAL_{WECCstates,m}$$

$$\sum_{dirty,n}^{n \in states} (CONVgen_{n,m,dirty} + CONVP_{n,m,dirty}) \leq \sum_n^{n \in states} L_{n,m}$$

**Generation from Low Sulfur Coal:** This constraint essentially adds all the coal used in the different time slices throughout the year into a single variable.

$$LOWSULCOAL_{n,q}$$

$$coalallowsul_{n,q \in coaltech} \leq \sum_m (CONVgen_{n,m,q} + CONVP_{n,m,q}) \cdot H_m$$

**SO<sub>2</sub> Scrubbers Constraint:** Combined capacity of the scrubbed and unscrubbed coal plants must be equal to the total of the two from the last period minus retirements. Furthermore, unscrubbed coal capacity can not exceed the unscrubbed capacity of the last period minus retirements. This allows the unscrubbed to become scrubbed, i.e., the unscrubbed capacity can decrease but the total can not. Scrubbed coal plants can be converted to cofiring via the same mechanism,

$$SCRUBBER_n$$

$$\begin{aligned} CONV_{n,scr} + CONV_{n,uns} + CONV_{n,cofire} &= CONVold_{n,scr} - CONVret_{n,scr} \\ &+ CONVold_{n,uns} - CONVret_{n,uns} \\ &+ CONVold_{n,cofire} \end{aligned}$$

-and-

$$CONV_{n,uns} \leq CONVold_{n,uns} - CONVret_{n,uns}$$

$$COFIRE\_CAPACITY_n$$

$$CONV_{n,scr} + CONV_{n,cofire} \geq CONVold_{n,scr} - CONVret_{n,scr} + CONVold_{n,cofire}$$

**Emissions Constraint:** Ensures that the national annual emission of each pollutant (CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub>, Hg) by all generators is lower than a national cap.

$EMISSIONS_{pol}$

$$\begin{aligned}
LP_{pol} \geq & \sum_{n,m,q} (CONVgen_{n,m,q} + CONVP_{n,m,q}) \cdot H_m \cdot CONVpol_{q,pol} \cdot CHEatrate_q \\
& + \sum_{n,m} STORout_{n,m,st} \cdot STORpol_{st,pol} \cdot CHEatrate_{st} \\
& - \sum_{\substack{q,n,pol \\ pol=SO_2}} coallowsul_{n,q} \cdot CONVpol_{q,pol} \cdot CHEatrate_q \cdot coallowsul_{polred} \\
& - \sum_{bioclass,n} CofireGen_{bioclass,n} \cdot CHEatrate_{cofire} \cdot (CONVpol_{coal,pol} - CONVpol_{biomass,pol})
\end{aligned}$$

**Geothermal Constraints:** These constraints regulate the expansion of geothermal capacity. Regional capacity is constrained by a recoverable capacity supply curve. Geothermal capacity, as shown below, is linked directly to  $CONV_{q,n}$  and, through it, the model's framework for dispatchable conventional technologies.

$GEO_THERMAL\_GROWTH_n$

$$\begin{aligned}
CONV_{n,geothermal} - CONVold_{n,geothermal} &= \sum_{geoclass} GeoBin_{geoclass,n} \\
&+ \sum_{egsclass} GeoEGSbin_{egsclass,n}
\end{aligned}$$

$GEO_THERMAL\_GROWTH\_BIN_{geoclass,n}$

$$GeoBin_{geoclass,n} + GeoOld_{geoclass,n} \leq GeoMax_{geoclass,n}$$

$GEOEGS\_GROWTH\_BIN_{egsclass,n}$

$$GeoEGSbin_{egsclass,n} + GeoEGSold_{egsclass,n} \leq GeoEGSmax_{egsclass,n}$$

**Biofuel Constraints:** These constraints regulate the capacity expansion of dedicated biomass and coal-biomass cofiring plants. Total bio-fired generation is limited by a regional feedstock supply curve. In cofired plants, biomass can contribute up to 15% of the feedstock. Biomass, like geothermal, is linked directly to the conventional variables such as  $CONV_{n,q}$  and  $CONVgen_{n,m,q}$ .

$BIOPOWER\_GROWTH_n$

$$CONV_{n,biopower} - CONVold_{n,biopower} = \sum_{bioclass} BioBin_{bioclass,n}$$

$COFIRE\_GENERATION_n$

$$\sum_{bioclass} CofireGen_{bioclass,n} \leq 0.15 \cdot \sum_{q,m} CONVgen_{n,m,cofire}$$

$BIOPOWER\_GENERATION_{bioclass,n}$

$$\begin{aligned}
& BioGeneration_{bioclass,n} \cdot CHEatrate_{biopower} + \\
& CofireGen_{bioclass,n} \cdot CHEatrate_{cofire} \leq BioSupply_{bioclass,n}
\end{aligned}$$